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Accumulation of soil organic carbon after cropland conversion to short-rotation willow and poplar

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Abstract

The demand for bioenergy has increased the interest in short-rotation woody crops (SRWCs) in temperate zones. With increased litter input and ceased annual soil cultivation, SRWC plantations may become soil carbon sinks for climate change mitigation. A chronosequence of 26 paired plots was used to study the potential for increasing soil organic carbon (SOC) under SRWC willow and poplar after conversion from cropland (CR) on well-drained soils. We estimated SOC stocks in SRWC stands and adjacent CR and related the difference to time since conversion, energy crop species, SOC stock of the adjacent CR (proxy for initial SOC of SRWC) and the fine soil percentage ($<63 \mu\text{m}$) (FS). Soil cores to 40 cm depth were sampled and separated by layers of fixed depths (0–5, 5–10, 10–15, 15–25 and 25–40 cm). Additionally, soils were sampled from soil pits by genetic horizons to 100 cm depth. Comparisons of SOC stocks by equivalent soil masses showed that mean SOC stocks in SRWC were 1.7 times higher than those of CR in the top 5 cm of the soil ($P < 0.001$). The differences between SRWC and CR remained significant for the plough layer (0–25 cm) by a factor of 1.2 ($P = 0.003$), while no changes were detectable for the 0–40 cm ($P = 0.32$), or for the entire 0–100 cm soil layer ($P = 0.29$). The SOC stock ratio, that is the ratio of SOC stock in SRWC relative to CR, did not change significantly with time since conversion, although there was a tendency to an increase over time for the top 40 cm ($P = 0.09$). The SOC stock ratio was negatively correlated to SOC in CR and FS percentage, but there was no significant difference between willow and poplar at any depth. Our results suggest that SOC stocks in the plough layer increase after conversion to SRWC.

Keywords: carbon, land-use change, paired plot chronosequence, poplar, short-rotation woody crop, soil organic carbon, time since conversion, willow

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Introduction

Biomass for bioenergy is one of the most flexible sources of renewable energy as it is storable and can be used for production of electricity, heat, and transport (Sartori *et al.*, 2006). Dedicated perennial energy crops such as willow (*Salix* spp.) and poplar (*Populus* spp.) managed with relatively frequent harvests compared to forest stands are more commonly known as short-rotation coppice (SRC), if managed with planting densities of 10 000–20 000 stems ha^{-1} and harvesting every 2–5 year. When managed with planting densities of about 2500 stems ha^{-1} and rotation ages of 10–30 years, it is known as short-rotation forestry (SRF). In this paper, the two types of systems are referred to as short-rotation woody crop (SRWC) systems, as earlier described by Agostini *et al.* (2015). The ability of these systems to achieve high yields in relatively short time spans is their

major asset as a bioenergy feedstock alternative to fossil fuel in the temperate regions.

The potential of SRWCs to reduce greenhouse gas emissions to the atmosphere is not limited to their role as substitutes for fossil fuels. It is hypothesized that they can also offset greenhouse gas emissions through increased soil carbon (C) sequestration following land-use change of agricultural land (Lemus & Lal, 2005). The dynamic fluctuations of soil C after afforestation on former arable land often display an initial decrease followed by an increase during the first decades, until the accumulation levels off with SOC stocks reaching the initial or higher SOC stock levels (Guo & Gifford, 2002; Poeplau *et al.*, 2011; Bárcena *et al.*, 2014a). SRWCs may not follow the same trajectory or timing as found during the early years after afforestation. They involve faster-growing species and are often grown with a denser stocking, and more frequent harvesting. The resulting high above- and belowground carbon inputs are linked to increased SOC stocks that have been reported in some studies only three to 15 years after conversion

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(Tolbert *et al.*, 2002; Arevalo *et al.*, 2011; Garten *et al.*, 2011; Harris *et al.*, 2015). Other studies report no change in SOC stocks during the first five to 19 years after conversion (Coleman *et al.*, 2004; Sartori *et al.*, 2007; Pacaldo *et al.*, 2013; Rytter, 2016).

Contrasting results in the literature may be due to variation in site-specific factors, which are strong co-drivers of soil C accumulation after conversion (Garten, 2002). The rate of C accumulation after conversion of cropland to SRWC has been reported to be negatively correlated to the initial C stock in cropland prior to conversion; that is, soils with lower initial C may have a higher affinity to accumulate C (Grogan & Matthews, 2002; Tolbert *et al.*, 2002; Garten, 2011; Rowe *et al.*, 2016). Many agricultural soils are depleted of C as a result of intensive management (Davidson & Ackerman, 1993; Richter *et al.*, 1999) and have been shown to have larger potential for soil C accumulation after conversion to SRWC compared to other land uses such as grasslands or other perennial crops (Poeplau *et al.*, 2011; Don *et al.*, 2012). Soils with higher clay and silt contents may have lower potential for C sequestration after conversion (Garten, 2002) because they often have high SOC stocks prior to conversion due to high aggregate stability and stronger protection of C in clay particles (Sorensen, 1981). Moreover, the specific perennial species influences the root distribution and the quality of the above- and belowground litter inputs, which may influence the decomposition rates and subsequent changes in SOC stocks (Baum *et al.*, 2009). Differences in management practices between poplar and willow, such as planting density or rotation length, may also lead to different litter and SOC accumulation rates after conversion (Rytter, 2012).

Only few studies of changes in SOC stock after conversion of cropland to SRWC have focused on temperate Scandinavian regions, although an increasing area of cropland has been converted to SRWC in this region. Denmark doubled the area of SRWCs to approx. 10 000 ha within a three-year period from 2010 to 2013 (Jørgensen *et al.*, 2013). This study aimed at assessing potential differences in SOC stocks in SRWC plantations and adjacent cropland in southern Scandinavia. The specific objectives were to determine the difference in SOC stocks between SRWC and adjacent cropland, with the cropland as a proxy for initial SOC stocks before conversion to SRWC, and investigate how the changes in SOC stocks after conversion to SRWC willow and poplar are related to site factors such as soil texture and initial SOC stocks. We hypothesized that SOC stocks in SRWC would be higher compared to adjacent cropland and that the difference between the two land uses increases with time since conversion, with accumulation rates depending on the species, willow or poplar. We

used a chronosequence of paired plots of SRWC and its adjacent cropland, under the assumption that SOC stocks of the cropland were in a steady state and accurately reflected the soil conditions of the SRWC plantation prior to its establishment. Comparisons of SOC stocks under different land uses may lead to over- or underestimations when analysed by fixed depth (Don *et al.*, 2011). Therefore, we evaluated the need to estimate SOC stock by equivalent soil masses (ESMs), as suggested by Lee *et al.* (2009) and Bárcena *et al.* (2014b).

Materials and methods

Site selection

This soil carbon survey was conducted in Denmark and southwestern Sweden (Table 1). The paired SRWC and cropland (CR) approach assumes that CR represents the initial SOC stock of SRWC prior to conversion. To conform to this assumption, the selection of the sample sites was based on the following criteria: (i) the SRWC should be planted on previous cropland with the same management history and similar soil properties as the adjacent cropland; (ii) the SRWC stands should not have been deep ploughed at conversion, as mixing of the plough layer with deeper soil layers would prevent comparisons between land uses when sampling to 40 cm depth; (iii) the SRWC and CR plots should be on well-drained soils with no anoxic conditions influencing the decomposition rate of organic matter; and (iv) sampled SRWC stands should, to the extent possible, cover a large range of years since conversion, a large range of different soil textures, and a wide geographical range within the region. In total, 26 suitable stands were identified and sampled, with time since conversion to SRWC ranging from 4 to 29 years. The sites included 18 willow and eight poplar stands (Table 1). Clear differences in management practices were observed between willow and poplar, with willow plantations generally being denser and managed in shorter rotation coppice (SRC), while most of the poplar plantations were planted at larger distances, and managed in longer rotations (SRF). All the sampled poplar stands were still in their first rotation after conversion from cropland.

Soil sampling took place during the summer periods of 2013 and 2014. The samples were collected both by fixed depth using soil cores and by genetic horizons from soil pits to 100 cm depth. Samples by fixed depths were initially collected using a Westman (1995) soil corer with an inner diameter of 45 mm (Ø) and a sampling depth of 50 cm (sites Tr, Ol1, Ol2, Sl, and Es, see Table 1). The rest of the sites were sampled using a split tube Eijkkamp soil corer with an inner diameter of 48 mm (Ø) and a sampling depth of 40 cm.

From each site, we sampled soils in two 20 × 20 m plots: the SRWC stand and its adjacent cropland. In each plot, a 10 × 10 m grid was laid out, resulting in nine intersections. A soil core sample was collected from each intersection. All samples were collected at a minimum distance of 5 m from the border between the field and the SRWC stand.

Table 1 Characteristics of the investigated sites, including their site names and associated abbreviations (Abbr.), geographical coordinates, soil percentage of clay (<2 µm) and silt (2–63 µm) in the C-horizon, sorted by species (sp.), willow (W) or poplar (P), and time since conversion (Time) from cropland (CR) to short-rotation woody crops (SRWCs)

Site	Abbr.	Coordinates		Sp.	Time (yr)	Clay (%)		Silt (%)	
		N	E			SRWC	CR	SRWC	CR
Olsted	Os	55°55'	12°30'	W	4	3.3	7.5	25.4	33.3
Christiansfeld	Cf	55°23'	9°24'	W	5	7.6	7.3	33.8	33.3
Olsted	Ol	55°55'	12°30'	W	6	3.7	7.5	19.7	33.3
Hadsten	Hd	56°21'	10°70'	W	7	0.3	0.0	4.8	0.0
Ansager	An	55°41'	8°42'	W	9	0.0	0.0	0.0	0.0
Allelev	Al	56°23'	10°45'	W	10	0.0	0.0	0.0	1.5
Bronderslev	Bd	57°14'	9°56'	W	11	3.1	0.0	32.3	0.0
Gistrup	Gs	56°57'	10°00'	W	12	3.7	4.3	23.7	23.4
Slangerup	Sg	55°51'	12°12'	W	13	3.3	9.7	18.4	57.0
Holstebro	Hb	56°24'	8°44'	W	14	2.0	1.3	18.5	9.7
Herning	Hr	56°12'	8°49'	W	15	0.0	0.0	1.2	1.0
Herning	Hn	56°12'	8°49'	W	16	0.1	0.0	3.3	1.0
Vodskov	Vs	57°70'	10°80'	W	18	0.0	0.0	5.0	4.1
Foulum	Fm	56°10'	9°47'	W	18	3.8	0.3	27.7	3.7
Tarm	Tm	55°51'	8°31'	W	19	1.4	2.8	9.4	17.1
Tvervangsvej	Tg	57°25'	9°56'	W	19	7.4	0.5	43.7	3.9
Tars	Ts	57°23'	10°40'	W	20	1.1	0.0	6.3	0.0
Eslov	Es	55°52'	13°16'	W	29	13.4	11.4	39.4	37.7
Brabrand	Bb	56°10'	10°30'	P	9	5.3	5.8	30.2	31.3
Vraa	Va	57°10'	9°56'	P	9	2.7	2.5	19.7	18.1
Frederikshavn	Fr	57°22'	10°25'	P	12	1.7	4.1	16.9	28.4
Brunbjerg	Br	55°48'	9°20'	P	14	0.0	0.4	0.0	6.6
Tvervangsvej	Tv	57°25'	9°55'	P	19	3.2	12.6	16.5	44.8
Vraa	Vr	57°11'	9°55'	P	19	2.9	2.5	23.2	18.1
Trolleholm	Tr	55°58'	13°80'	P	23	12.6	8.8	70.1	59.3
Hals	Hs	57°10'	10°18'	P	28	0.0	0.0	0.0	0.0

All sites were located in Denmark, except Es and Tr, which were located in southern Sweden.

The soil cores were separated into five subsamples each representing a layer of a fixed depth (0–5, 5–10, 10–15, 15–25, and 25–40 cm). We observed variation in the ploughing depth between sites, with all plots ploughed to a minimum depth of 25 cm. Due to soil compaction, the number of soil cores was only six in the poplar plot of the Bb site (Table 1). For each site and soil layer, three soil cores were pooled together by sample grid row into one composite sample, resulting in three pseudoreplicates for the estimation of bulk density.

A soil pit was dug in the centre of the sampling grid, and genetic horizons were determined after performing a soil profile description. A composite sample for each genetic horizon consisted of three subsamples collected with a soil ring ($l = 54$ mm, $\varnothing 48$ mm). There were no soil pit sampling in the Bb site, and the Tr and Br cropland fields (Table 1), resulting in 23 sites with complete paired soil pit sampling.

Sample preparation

Soil samples were air-dried at room temperature for at least a week. The soil aggregates were crushed and sieved using a

2-mm sieve. The coarser roots and stones (>2 mm) were removed and weighed. The total stone content in the samples ranged between 0% and 12% volume, except site Al with a mean stone content of 18% in the top 40 cm. On all sites, the stone content was gravel-sized, with no larger stones or rocks disturbing the sampling, the plant growth or the root development. The sieved soil samples were oven-dried at 55 °C until constant weight. The dry samples were weighed on a Mettler Toledo PG5002-S Delta Range Balance. After weighing for the bulk density determination, the three pseudoreplicates were pooled into one composite sample and mixed thoroughly. Once the homogenization of the soil sample was complete, a subsample was further ground in a Retsch PM 400 ball mill for carbon concentration determination.

Chemical analyses

The soil pH was measured in a suspension of 10 g soil and 25 mL 0.01 M CaCl₂ using a glass calomel electrode GK2401 (Radiometer, Copenhagen, Denmark). For samples with pH higher than five, presence of calcium carbonate was tested and, if present, was removed prior to analysis of organic C.

Subsamples of 20 mg were weighed and placed in silver (Ag) cups that were warmed at 70 °C on a Keratherm, 4800-Watt thermal plate. Presence of calcium carbonate was tested by adding sulphurous acid (H₂SO₃) as a 6% solution (W/V) (Skjemstad & Baldock, 2007). If effervescence occurred, H₂SO₃ addition continued until the inorganic carbon was completely removed and the samples stopped effervescing. Thereafter, the samples were left to air-dry overnight. The total carbon and nitrogen concentrations were determined for all samples by dry combustion, based on the Dumas method using a 'FLASH 2000 EA NC' analyser (Thermo Fisher Scientific, Waltham, MA, USA) (Matejovic, 1993).

The texture of the soil was determined from the C-horizon or the deepest sampled soil layer of the soil pit, to best describe the inherent pedogenic properties on each site. The texture was determined by laser diffraction (Malvern Hydro 2000 G). After mixing the soil sample for a minute, 50 g of soil was weighed and sieved through a 1.2 mm sieve and the two fractions were weighed again to determine the percentage of soil particles smaller than 1.2 mm. A spoonful of soil less than 1.2 mm was dispersed in a sodium pyrophosphate decahydrate 0.01 M (0.245%) solution and washed and diluted with distilled water in a plastic cup before inserted into an ultrasound bath (Bandelin Sonopuls HD 2200 max power) for two minutes, where after it was inserted into the laser diffractometer. Five analyses were carried out and averaged to determine the particle size distribution. The summed percentage of clay (<2 µm) and silt (2–63 µm) of the C-horizon (or the lowest sampled genetic horizon) were used to represent the fine soil percentage (FS) of each site.

Calculations

The soil mass without stones (<2 mm), SM_{ijk} [Mg ha⁻¹], for each site, i , land use, j , and soil layer, k , was calculated as

$$SM_{ijk} = h \cdot r^2 \cdot \pi \cdot BD_{ijk} \quad (1)$$

where h is the height of the cylinder representing the soil layer, $k = 0-5, 5-10, 10-15, 15-25$, and $25-40$ cm, r is the radius of the cylinder, and BD_{ijk} is the bulk density of the soil (<2 mm). BD_{ijk} [g cm⁻³] was estimated as

$$BD_{ijk} = \frac{W_{soil}}{V_{soil} - \left(\frac{W_{stone}}{BD_{stone}} \right) - \left(\frac{W_{root}}{BD_{root}} \right)} \quad (2)$$

where W_{soil} and V_{soil} are the total weight and volume of the soil sample (<2 mm), respectively. The stone bulk density, BD_{stone} , was set to 2.65 g cm⁻³ (Brady & Weil, 2012), while the basic density of roots, BD_{root} , was assumed to be 0.35 g cm⁻³ based on comprehensive measurements of basic densities of poplar aboveground stem biomass (Taerwe *et al.*, 2015). The root biomass was usually negligible.

The SOC stocks were estimated as the product of the soil mass and the C concentration for each soil layer, k , site, i , and land use, j . Analyses of the factors affecting changes in BD (see details in 'Section 2.5', Eqn 7) suggested that comparison of SOC stock by ESM was more appropriate than by fixed soil depths. SOC stocks were consequently corrected by the use of the minimum (ESM) method (Lee *et al.*, 2009). For each site, i ,

and accumulated soil layer, d (0–5, 0–10, 0–15, 0–25, and 0–40 cm), the soil mass corresponding to the lightest of the two plots (land uses), $SOC_{id(light)}$ [Mg ha⁻¹], was used as the reference mass. The difference in soil mass, ΔSM_{id} [Mg ha⁻¹], between the original mass of accumulated soil layer d , $SM_{id(ori)}$, and the lightest reference soil mass $SM_{id(light)}$, was estimated as

$$\Delta SM_{id} = SM_{id(ori)} - SM_{id(light)} \quad (3)$$

The SOC stocks for the adjusted plot were then estimated as

$$SOC_{ijd} = SOC_{ij(d-1)} + C_{ijk} \cdot (SM_{ik} - \Delta SM_{id}) \quad (4)$$

where $SOC_{ij(d-1)}$ is the sum of the product of the soil mass and the C concentration for all layers, k , of the accumulated layer, $d - 1$, for site, i , and the land use with adjustment, j . C_{ijk} (%) is the C concentration of the site, i , land use with adjustment, j , for the last soil layer, k of the accumulated layer, d . $(SM_{ik} - \Delta SM_{id})$ is the adjusted soil mass of the land use with adjustment, j , in each site, i , for accumulated layer, d , where SM_{ik} is the soil mass of the last soil layer, k , included for accumulated layer, d .

The soil characteristics of CR were used as a proxy for the initial soil characteristics of the SRWC, and the ratio (R) between a certain soil characteristic, Y , of the two land uses was thus assumed to express the relative change after conversion:

$$R_Y = Y_{SRWC} / Y_{CR} \quad (5)$$

where Y represents C concentration (C), bulk density (BD), pH, C/N ratio (C/N) or SOC stocks corrected by ESM (SOC). Analysing R_Y instead of absolute values was a way to normalize the data and compare measurements across sites.

Statistical analyses

The main aim of the analyses was to detect effects on R_{SOC} of time since conversion, species, SOC_{CR} , and FS percentage. We used linear models (Eqn 6) to test whether these factors were confounded, as this would limit the interpretation with regard to causality of the individual independent factors. In total, six tests were made:

$$Y = \beta_0 + \beta_1 X + \varepsilon \quad (6)$$

where Y is one of the four independent variables and X is one of the three remaining.

The relationship between mean bulk density of each site and soil layer (BD_{ik}) with C concentrations (C_{ik}) (%), fine soil percentage (FS), and land use (LU) was tested, where LU was SRWC or CR. Starting with a full model, backward selection was used to reduce the model until only significant terms were left:

$$BD_{ik} = \beta_0 + \beta_1 C_{ik} + \beta_2 FS + \beta_3 LU + \varepsilon \quad (7)$$

The soil characteristic ratios, R_Y , were tested in a linear model to determine whether ratios were significantly different from 1.0, to determine differences between the land uses. Analyses for each soil characteristic were performed for the separate soil layers, k (0–5, 5–10, 10–15, 15–25, and 25–40 cm).

The SOC stock ratio, R_{SOC} , was first modelled against SOC_{CR} , as a proxy for the initial SOC stock SRWC, FS percentage, and their interaction, in an analysis of covariance (ANCOVA)

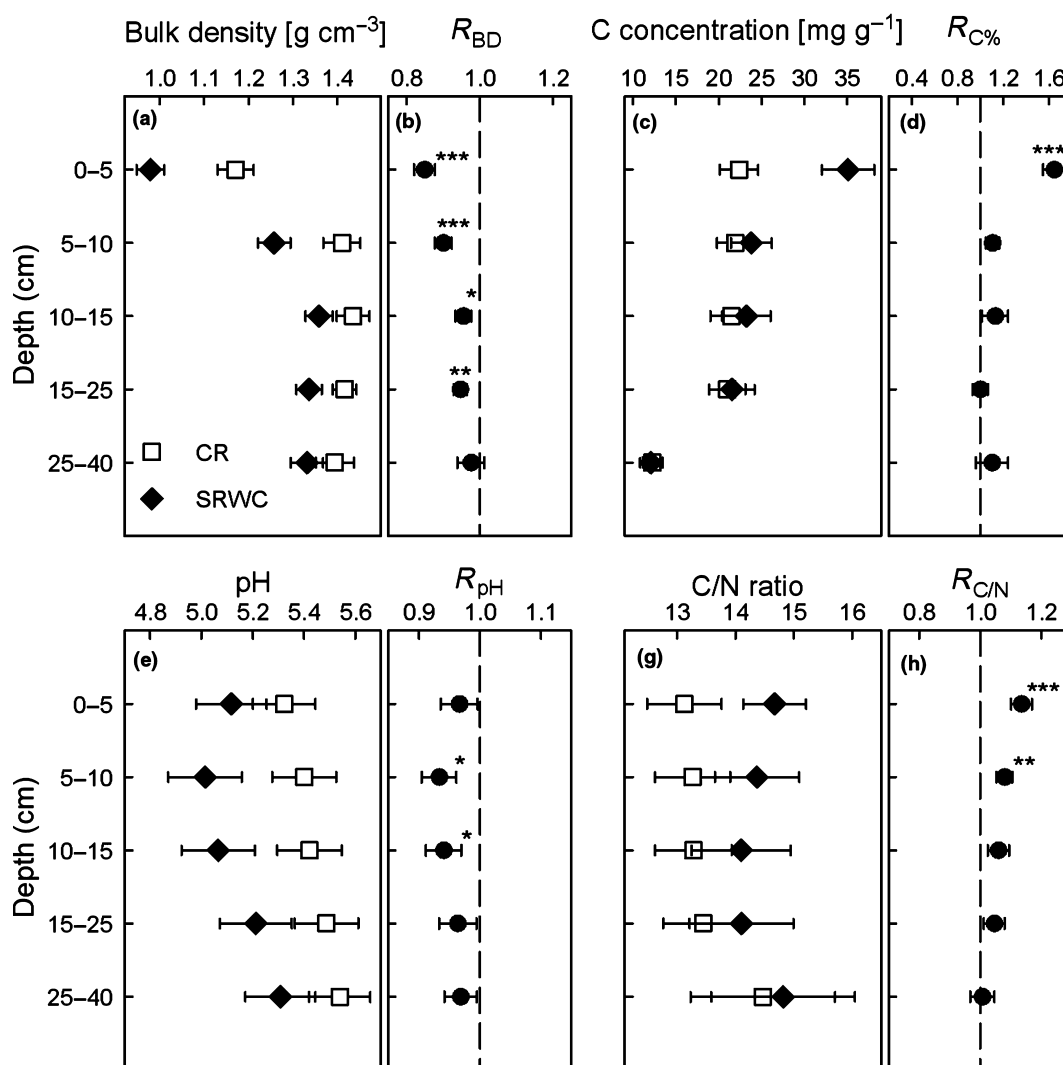


Fig. 1 Mean bulk density (a), C concentration (C), pH (e), and C/N ratio (g) of soil in short-rotation woody crops (SRWCs) and cropland (CR), respectively, and corresponding ratios (R) between SRWC and CR for bulk density (b), C concentration (d), pH (f), and C/N ratio (h) for different soil layers. Ratios were different from 1.0 at the following significance levels: *** $P < 0.001$; ** $P < 0.01$; * $P < 0.05$. Error bars show the standard error of the means.

to determine the variation deriving from immanent soil characteristics. Tests were made for R_{SOC} of different accumulated soil layers, d (0–5, 0–10, 0–15, 0–25, and 0–40 cm, $df = 21$):

$$R_{SOC} - 1 = \beta_0 + \beta_1 SOC_{CR} + \beta_2 FS + \beta_3 SOC_{CR} FS + \varepsilon \quad (8)$$

The analysis was further expanded to include the time since conversion (time) and the energy crop species (sp), willow or poplar, by subtracting the modelled values from Eqn (8) from the measured values. These residuals were then modelled against time and sp ($df = 23$):

$$\varepsilon_{Eqn.8} = \beta_0 + \beta_{sp} + \beta_1 time + \varepsilon \quad (9)$$

The software R version 3.1.1 was used for all statistical analyses.

Results

Assumptions and orthogonality of independent variables

FS percentages of the paired land uses were not significantly different ($P = 0.87$), indicating no preferential choice for conversion of cropland to SRWC based on soil texture. There was no correlation between time since conversion and FS percentage ($P = 0.39$). However, SOC decreased with increasing FS percentage. The results were consistent across all soil layers with the highest variability explained in the accumulated 0–40 cm layer ($P = 0.01$, $r^2 = 0.24$).

Table 2 Parameter estimates and statistics of models for soil bulk density (BD) as a function of C concentration (mg g^{-1}) (C) and fine soil percentage (FS) (Eqn 7). Only significant effects were included

Layer	Coefficients	df	Estimate	SE	P	r^2
0–5 cm	Intercept	48	1.34	0.064	<0.001	0.35
	C		−0.005	0.002	0.007	
	FS		−0.003	0.001	0.032	
	LU _(SRWC)		−0.125	0.053	0.022	
5–10 cm	Intercept	48	1.689	0.073	<0.001	0.33
	C		−0.009	0.002	<0.001	
	FS		−0.004	0.001	0.003	
	LU _(SRWC)		−0.132	0.048	0.008	
10–15 cm	Intercept	49	1.598	0.057	<0.001	0.23
	C		−0.006	0.002	0.001	
	FS		−0.003	0.001	0.008	
	LU _(SRWC)		−0.074	0.031	0.023	
15–25 cm	Intercept	48	1.624	0.046	<0.001	0.42
	C		−0.007	0.001	<0.001	
	FS		−0.002	0.001	0.008	
	LU _(SRWC)		−0.074	0.031	0.023	
25–40 cm	Intercept	51	1.362	0.028	<0.001	

C concentration, bulk density, pH, and C/N ratio

Soil characteristics generally differed significantly between CR and SRWC, with the greatest differences occurring in the top layers (Fig. 1). The bulk density in SRWC in the top 5 cm ranged from 0.7 to 1.2 g cm^{-3} , and in CR the values were between 0.8 and 1.7 g cm^{-3} . Bulk density tended to increase with depth in both SRWC and CR until a depth of about 15 cm and thereafter remained constant (Fig. 1a). The BD ratio, R_{BD} , was significantly lower than 1.0 in all soil layers to a depth of 25 cm (Fig. 1b), indicating generally lower bulk density values for SRWC compared to CR.

The C concentration in the top 5 cm ranged from 11 to 68 mg g^{-1} in CR, and from 15 to 82 mg g^{-1} in SRWC. In CR, the C concentration was similar down to 25 cm, and only in the 25–40 cm layer it decreased (Fig. 1c). In SRWC, the C concentration in the top 5 cm was higher than in deeper soil layers (Fig. 1c). The mean C concentration ratio, R_{C} , was significantly higher than 1.0 in the top 5 cm ($R_{\text{C}} = 1.6$, $P < 0.001$), indicating higher C concentrations in the topsoil of the SRWC stands compared to CR. The R_{C} in the 5–10 cm layer tended to be higher than 1.0 ($R_{\text{C}} = 1.1$, $P = 0.08$). No differences were found in the deeper soil layers (Fig. 1d).

The pH values of the top 5 cm ranged from 3.5 to 7.1 for SRWC plots and from 3.9 to 6.7 for CR. The mean values of pH in the SRWC tended to be lower than those of CR in all soil layers (Fig. 1e), but the pH ratio, R_{pH} , was only significantly lower than 1.0 in the 5–10 cm and 10–15 cm layers ($P = 0.02$ and $P = 0.05$, respectively) (Fig. 1f).

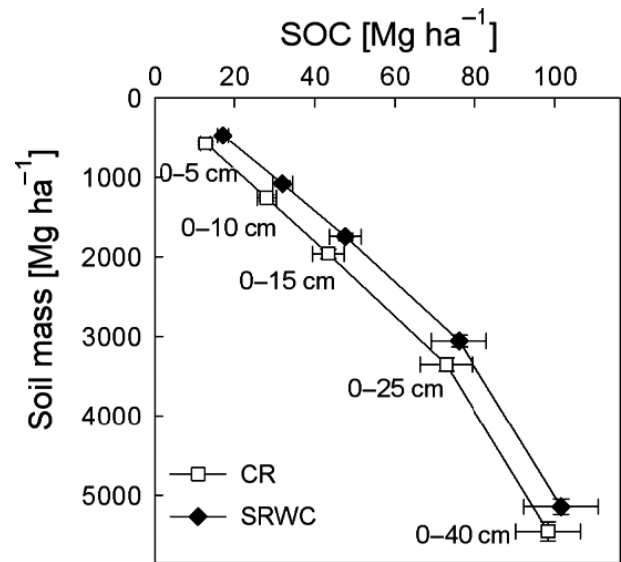


Fig. 2 Mean accumulated soil organic carbon (SOC) stock and corresponding mean accumulated soil mass for different soil depths under short-rotation woody crops (SRWCs) and cropland (CR). Bars show standard error of the mean.

For SRWC, the C/N ratio tended to decrease down to the 15–25 cm layer and then increase again (Fig. 1g). The relative C/N ratio ($R_{\text{C/N}}$) was significantly higher than 1.0 in the 0–5 ($P < 0.001$) and 5–10 cm layers ($P = 0.002$) but approached values of 1.0 with increasing depth (Fig. 1h).

Bulk density correlation with C concentration and land use

For BD, we found no interactions between the analysed independent variables in any soil layer (Table 2). The BD was negatively correlated to C concentration and FS percentage in all soil layers. For the layers 0–5, 5–10, and 15–25 cm, additional variation could be attributed to LU. This highlighted the importance of using the SOC stock corrected by ESM (Table 2).

SOC stocks by fixed depth

A high variation in SOC stocks was found between sites. The SOC stock in the top 40 cm ranged between 50 and 241 Mg ha^{-1} in CR and between 37 and 244 Mg ha^{-1} in SRWC. Visual inspection of Fig. 2 suggested that the SOC stocks were generally higher in SRWC compared to CR for all accumulated soil layers, while the soil mass was lower in SRWC compared to CR for the same layer. The largest differences between SRWC and CR in SOC stocks seemed to be in the top layers. The mean SOC stock in SRWC in the top 5 cm was 4.3 Mg ha^{-1} higher than in CR, while the mean

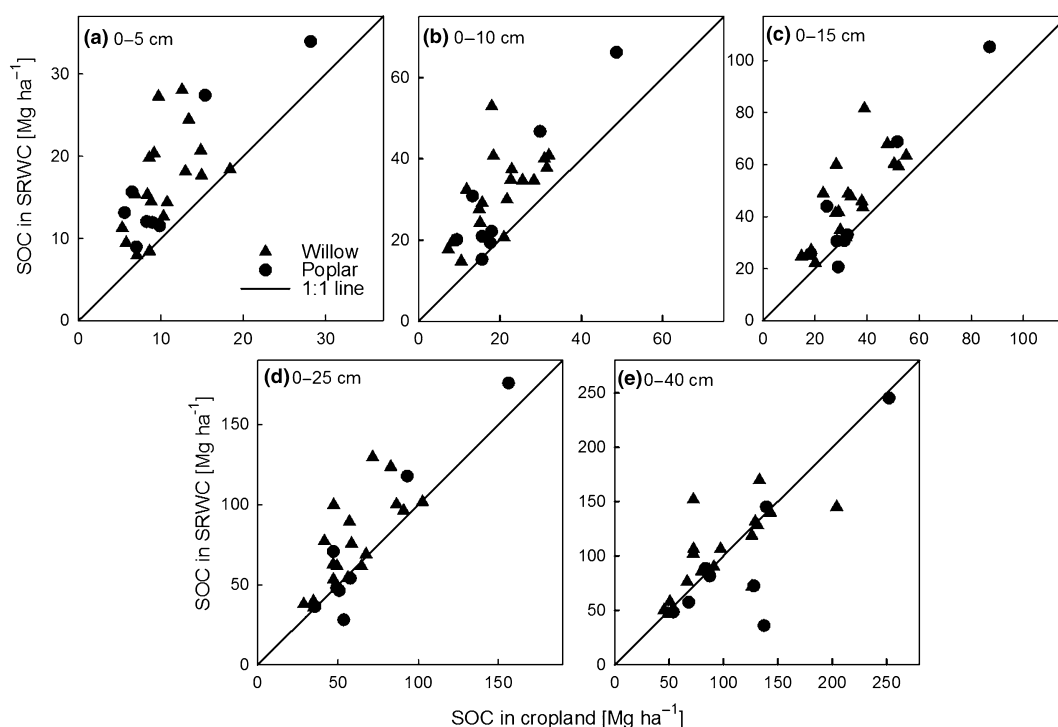


Fig. 3 Soil organic carbon (SOC) stock, estimated by the ESM method, under short-rotation woody crops (SRWCs) and cropland (CR) of the accumulated (a) 0–5 cm, (b) 0–10 cm, (c) 0–15 cm, (d) 0–25 cm, and (e) 0–40 cm soil layers.

difference was only 3.2 Mg ha⁻¹ for the 0–40 cm layer. The mean soil mass in SRWC of the top 5 cm was 100 Mg ha⁻¹ lower than in CR, with this difference increasing to 307 Mg ha⁻¹ for the 0–40 cm layer (Fig. 2). The differences in soil mass between the two land uses until a certain depth again indicated that comparisons of the two land uses by ESM were preferable to comparisons by fixed depth (see supporting information for statistical analysis by fixed depth, Fig. S1).

SOC stocks by equivalent soil mass

When analysed by ESM, the mean SOC stock in SRWC was significantly higher than in CR in the top 5 cm, with a mean R_{SOC} of 1.7 ($P < 0.001$) (Fig. 3). The difference remained significant in the accumulated 0–10 cm, 0–15 cm, and 0–25 cm layers by factors of 1.7 ($P < 0.001$), 1.4 ($P < 0.001$), and 1.2 ($P = 0.003$), respectively, but not for the 0–40 cm layer ($P = 0.64$).

The SOC stock ratio, R_{SOC} , estimated by ESM, showed a negative correlation with SOC_{CR} and FS percentage in the different soil layers (see Supporting Information for correlations between FS percentage and SOC_{CR} , Fig. S2). SOC_{CR} and FS percentage and their interaction explained between 3% and 27% of the R_{SOC} variation, respectively (Table 3). The residuals of these models

were not related to time since conversion for any given accumulated soil layer, even if there was a tendency to an increase with time for the 0–40 cm (Fig. 4). Lastly, there were no significant differences in R_{SOC} between poplar and willow at any depth.

SOC stocks in soil pits

The mean SOC stock down to 100 cm depth was 120 Mg C ha⁻¹ in CR and 127 Mg C ha⁻¹ in SRWC. There was no significant effect on R_{SOC} of the time since conversion, and the ratio was not significantly different from 1.0 ($P = 0.29$). Thus there was no detectable change in SOC stocks between SRWC and CR of the accumulated 0–100 cm layer (Fig. 5).

Discussion

C concentration, C/N and pH

Homogenization of the top soil through mechanical mixing results in uniform C concentrations in cropland where soils are tilled on an annual basis. The higher C concentration in the top layers of SRWC and the development of a C concentration gradient with soil depth is presumably due to cessation of tillage and increased litter inputs in SRWC compared to CR. These results are

in accordance with Jug *et al.* (1999) who found a clear gradient in C concentrations in the top layers and lower values in deeper layers after conversion from cropland to short-rotation plantations in Germany. Dimitriou *et al.* (2012) also found increased C concentrations in SRWC compared to cropland in the top 20-cm soil layer in Sweden. The higher C concentration was also reflected in the C/N ratio, which was significantly higher in the 0–5 cm and 5–10 cm layers in SRWC compared to CR. Cessation of frequent fertilizer inputs may further increase C/N ratios due to uncompensated N uptake from the soil by the energy crops and subsequent biomass and N removal. In agreement with this, Rong *et al.* (2010) found increased C/N ratios after conversion of cropland to poplar plantations. The C/N ratio in SRWC in our study, though higher than in CR, was still low, which indicated rapid decomposition and slow accumulation rates of SOC after conversion to SRWC.

The lower pH in SRWC was most likely caused by cessation of regular liming. Unfortunately, no record of liming frequency was available for the sampled sites, but previous studies also reported decreased pH after cropland conversion to willow and poplar plantations (Jug *et al.*, 1999; Keith *et al.*, 2015). Other possible explanations involve increased litter input and decomposition, and therefore, increased production of CO₂ and organic acids (Richter *et al.*, 1994; Bolan & Hedley, 2003; Holubik *et al.*, 2014). Berthrong *et al.* (2009) further ascribed acidification of soils after afforestation to increased uptake of cations (Mg²⁺, Ca²⁺, K⁺) by the trees, leading to decreased base saturation.

Bulk density

The low bulk densities in SRWC compared to cropland in the top soil layers were consistent with findings of Tolbert *et al.* (2002), Coleman *et al.* (2004), and Rong *et al.* (2010). Bulk density changes are primarily driven by C content and soil texture (Callesen *et al.*, 2003; De Vos *et al.*, 2005), but our results indicated that changes in bulk density could also be attributed to other land-use change factors. Decreased bulk density can derive from cessation of frequent use of machinery and increased root development (Greacen & Sands, 1980; Markewitz *et al.*, 2002; Rong *et al.*, 2010). Such changes in bulk density result in changes in soil mass and therefore noncomparable SOC stocks at fixed depths, and highlight the relevance of analysing SOC by (ESM). A few studies have accounted for such changes and compared SRC to cropland by ESM (Rong *et al.*, 2010; Walter *et al.*, 2015; Ferchaud *et al.*, 2016; Rowe *et al.*, 2016), but they show no consistent

Table 3 Parameter estimates and statistics of the model for the soil organic carbon (SOC) stock ratio, R_{SOC} , between short-rotation woody crop (SRWC) and cropland (CR) for different accumulated soil layers having SOC in CR, SOC_{CR} (Mg ha⁻¹) (the proxy of initial SOC in SRWC) and fine soil percentage (FS) as independent variables (df = 21, Eqn 8)

Layer	Coefficients	Estimate	SE	P	r ²
0–5 cm	Intercept	2.55	0.38	<0.001	0.27
	SOC_{CR}	−0.05	0.02	0.042	
	FS	−0.02	0.02	0.458	
	FS* SOC_{CR}	0.00	0.00	0.785	
0–10 cm	Intercept	2.07	0.49	0.039	0.03
	SOC_{CR}	−0.01	0.01	0.412	
	FS	0.01	0.02	0.606	
	FS* SOC_{CR}	0.00	0.00	0.676	
0–15 cm	Intercept	1.81	0.27	0.007	0.15
	SOC_{CR}	−0.01	0.00	0.173	
	FS	−0.02	0.02	0.129	
	FS* SOC_{CR}	0.00	0.00	0.237	
0–25 cm	Intercept	1.71	0.24	0.007	0.26
	SOC_{CR}	0.00	0.00	0.099	
	FS	−0.03	0.01	0.032	
	FS* SOC_{CR}	0.00	0.00	0.084	
0–40 cm	Intercept	1.45	0.27	0.111	0.17
	SOC_{CR}	0.00	0.00	0.094	
	FS	−0.02	0.01	0.154	
	FS* SOC_{CR}	0.00	0.00	0.337	

The model residuals were further used to explore the effects of time since conversion (Fig. 4).

direction of change in bulk density. For example, Walter *et al.* (2015) found no or very small variation in bulk density between SRC and CR, whereas Rowe *et al.* (2016) and Ferchaud *et al.* (2016), in contrast to our results, reported higher bulk densities in the bioenergy crops compared to CR. Management practices such as tillage in cropland can significantly reduce the soil bulk density (Ellert & Bettany, 1995; Lee *et al.*, 2009). Whether sampling of cropland is implemented before or after tillage may thus affect the results in bulk density and hence the soil mass. Such alterations are factors leading to uncertain estimations of SOC stocks if estimated by fixed depth and not by ESM.

SOC stock changes after conversion to SRWC

The greatest differences in SOC stocks between CR and SRWC were found in the top soil layers. The differences decreased as more layers were included, ending with no significant difference in 0–40 cm. The increased C stock in the top layers is in accordance with previous studies for the top 5-cm (Ferchaud *et al.*, 2016), 10-cm (Tolbert *et al.*, 2002; Pellegrino *et al.*, 2011; Lockwell

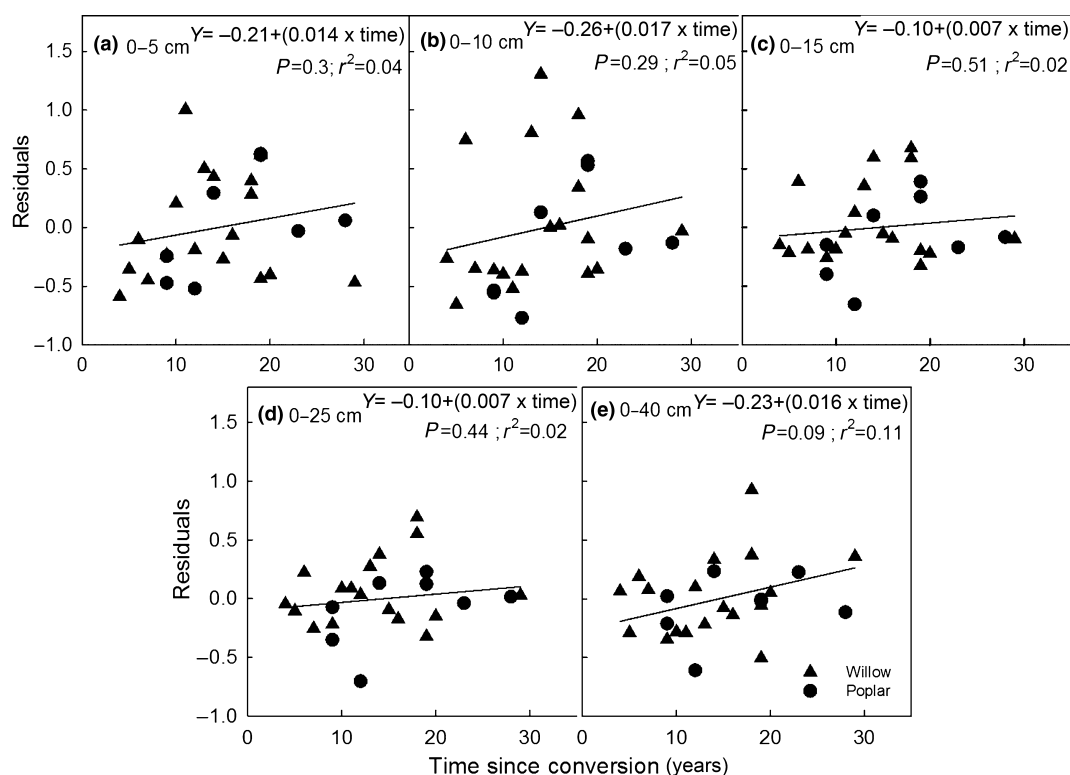


Fig. 4 Residuals of the measured soil organic carbon (SOC) stock ratio, R_{SOC} , after modelling R_{SOC} (Table 2) with time since conversion as independent variable (Eqn 9) for the accumulated (a) 0–5 cm, (b) 0–10 cm, (c) 0–15 cm, (d) 0–25 cm, and (e) 0–40 cm layers.

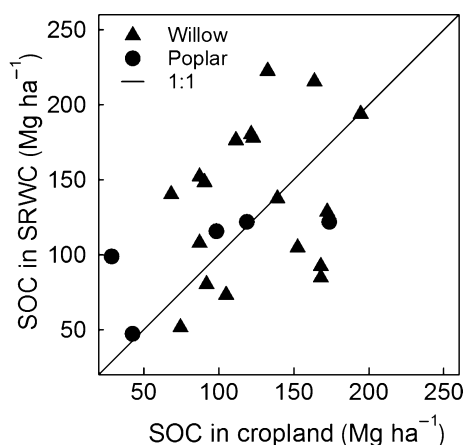


Fig. 5 Soil organic carbon (SOC) stocks in short-rotation woody crops (SRWCs), SOC_{SRWC} , and cropland (CR), SOC_{CR} , for the 0–100 cm layer, sampled by genetic horizons in the soil pits.

et al., 2012; Walter *et al.*, 2015) or even 20-cm soil layers (Ceotto & Candilo, 2011), but fewer studies have shown changes in soil C to lower soil depths. Walter *et al.* (2015) studied 18 paired sites with SRC and cropland in central Europe 8–35 years after conversion, and Rowe

et al. (2016) studied 12 sites in the United Kingdom with poplar or willow stands 4–23 years after conversion. None of the two studies showed any significant increase in SOC stock of the 0–30 cm layer after conversion. In agreement with this, Rong *et al.* (2010) did not find a significant change in SOC stock down to 30 cm in a chronosequence study of marginal agricultural land converted to poplar plantations in China. Using a sampling depth of 25 cm in this study, instead of 30 cm, may have reduced the probability of including soil below the plough layer, thereby reducing variation occurring from the inclusion of deeper soil layers.

Cessation of tillage after cropland conversion to poplar or willow plantations has previously been argued to cause redistribution of soil C within the plough layer (Walter *et al.*, 2015; Rowe *et al.*, 2016). Increased SOC stock in the top layers, but not in the accumulated 0–40 cm layer, could indicate redistribution (Fig. 3). However, we found higher C concentrations and lower BD in top layers in SRWC, but no sign of lower C concentration or higher BD in deeper layers (Fig. 1). This suggests that the decrease in R_{SOC} , with increasing accumulated depth, was not due to redistribution, but rather due to a dilution effect. Increased SOC stocks in the top soil may be due to the perennial nature of poplar and willow

plantations that generally results in increased litter inputs compared to annually harvested crops (Ferchaud *et al.*, 2016). Additionally, it is possible that cessation of tillage reduces C decomposition, due to reduced aeration of the soil (Kahle *et al.*, 2013).

Effects of time since conversion, initial SOC, soil texture, and energy crop species

We did not find increasing SOC stocks with time since conversion, neither for poplar nor willow. Other studies found an increasing C accumulation with time since conversion and ascribed this to the litter input exceeding the decomposition rates (Tolbert *et al.*, 2002; Arevalo *et al.*, 2011; Garten *et al.*, 2011; Harris *et al.*, 2015). Previous research on SRC has reported accumulation rates of 0.3 Mg C ha⁻¹ yr⁻¹ in Germany (Hellebrand *et al.*, 2010), and even up to 1.0 and 1.6 Mg C ha⁻¹ yr⁻¹ under hybrid poplar plantations in Canada and the USA, respectively (Hansen, 1993; Arevalo *et al.*, 2011). Our results remain inconclusive as the overall SOC stock was higher for SRWC, but a correlation with time since conversion could not be established, likely due to large variation.

Generally, there was a negative correlation between the SOC stock ratio and the SOC stock in cropland (SOC_{CR}) and the FS percentage, and a correlation between SOC_{CR} and FS percentage for all soil depths. Similarly, Tolbert *et al.* (2002) found minimal SOC changes on sites with high initial SOC stocks after conversion of cropland to switchgrass and sweetgum for bioenergy production in the USA, and increased SOC stocks on sites with low initial SOC levels. Results by Rowe *et al.* (2016) also indicate the influence of the initial SOC stock for SOC accumulation following conversion to perennial bioenergy crops. SOC_{CR} was included as a proxy of initial SOC in SRWC, which also varied due to influence on SOC levels of different management practices (residue removal vs. ploughing residues down, or rotation cultivation) and agricultural crop types (e.g. nitrogen fixing crops) applied before conversion (Paustian *et al.*, 1997).

The comparable SOC stock ratios of SRWC poplar and willow indicated that differences in planting densities, rotation lengths or litter quality were of minor importance. Only few studies addressed differences between energy crop species. In Italy, Ceotto & Candilo (2011) found no differences in SOC stocks of the 0–20 cm and 20–40 cm layers between poplar and willow 20 years after conversion. Qin *et al.* (2016) also did not detect any differences in SOC stock between poplar and willow energy crops. Our sampling design and available information about the field management did not allow further investigation of possible effects of site productivity,

rotation length, the number of rotations since conversion and plant density on accumulation of SOC.

SOC stocks in the top 100 cm

We found no overall differences in SOC stocks between CR and SRWC for the 0–100 cm layer, which is consistent with no detectable change in 25–40 cm and results of other studies examining changes below the plough layer (Coleman *et al.*, 2004; Walter *et al.*, 2015). Fine roots, with faster turnover rates, are more concentrated in the upper layers of the soil, whereas there are relatively more coarse roots in the deeper layers, which remain intact for longer periods (Pacaldo *et al.*, 2013). In a global meta-analysis, Qin *et al.* (2016) accordingly showed that SOC changes after cropland conversion to SRWC are more pronounced in the upper 30-cm soil layer compared to deeper layers. While SOC stocks in the subsoil are usually less sensitive to land-use change (Guo & Gifford, 2002; Poeplau & Don, 2013), some studies highlight the importance of sampling deeper layers, particularly in long-term studies, as significantly higher SOC stocks have been found in perennial crops compared to annually tilled cropland to a depth of 90 cm, with large proportions of the total C stored below 30 cm depth (Gauder *et al.*, 2016). However, sampling in soil pits is usually limited to one or few pits within a field and therefore cannot capture and separate within site variability from variability due to land-use change.

Our study suggests that conversion of cropland to SRWC increases SOC stocks in the former plough layer during the first decades, starting from the top of the former plough layer. Therefore, SOC stock changes may be overlooked when sampling the former plough layer in one segment. We found that the SOC accumulation depended on the initial SOC stocks (i.e. the proxy SOC_{CR}) and soil texture. These results may be of particular interest to future studies aiming at further explaining the exact processes of SOC accumulation, and as empirical evidence for future modelling of SOC changes. While we found higher SOC levels in SRWC compared to CR, our initial hypotheses were not confirmed; we did not find a correlation between SOC stock changes and time since conversion, or a difference in accumulation of SOC between SRWC poplar and willow. Further information regarding the influence of site productivity and management history could likely improve future analyses and our current understanding of SOC accumulation processes.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Figure S1. Soil organic carbon (SOC) stocks estimated by fixed depth in short rotation woody crops (SRWCs) and adjacent cropland (CR).

Figure S2. Soil organic carbon (SOC) stocks in cropland (CR) fields plotted against the corresponding fine soil percentage (FS) on the 0–40 cm layer.